A Multi-Dimensional Transient Mathematical Model of Blast Furnace Based on Multi-Fluid Model(多流体モデルに基づく高炉の多次元非定常モデル)

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論文内容要旨

The blast furnace is a multi-phase counter current moving bed reactor whose main purpose is to produce pig iron from iron oxides. The inputs in the blast furnace are the burden materials and hot blast. The outputs are hot metal, molten slag and exit gas. The burden materials are usually composed of coke, sinter, iron ore and pellets. The blast is composed of nitrogen, oxygen, water vapor and often some auxiliary gaseous fuel like natural gas. The oxygen in the blast reacts with coke and auxiliary fuels, generates carbon monoxide and hydrogen, which reacts with the iron oxides working as reducing gas. The burden materials descends in the blast furnace, undergo chemical reactions and phase transformations generating hot metal and slag. The blast furnace process has experienced tremendous developments in the last decades. This has been possible due to continuous development of the instrumental control and mathematical models, which have increased the knowledge of the blast furnace operators and made possible the introduction of new technologies aiming to increase the productivity and decrease the energy consumption. Previous blast furnace models have considered up to four phases in the blast furnace (solids, gas, liquids and powders). However, thermophysical properties of slag and hot metal, like density, viscosity, specific heat and thermal conductivity are quite different each other. The fine ore or flux injected through the blast furnace tuyeres or generated internally by degradation process also pursue different properties. Therefore, these materials need to be considered as different phases possessing own motions, energy and phase composition. Although various mathematical models of the blast furnace have been reported in previous literatures, most have made many simplifications to the governing equations, and several important blast furnace features like three-dimensional and transient behaviors have been ignored. In this thesis, a mathematical model, which does consider the three-dimensional transient behavior of the blast furnace with six major phases simultaneously interacting via multiphase chemical reactions and physical changes, was developed. The most remarkable advances of this model over previous ones are three-dimensional and transient treatments and other phases and chemical species were newly introduced to take into account the different behavior of liquid phases like hot metal and slag and powder phases such as pulverized coal and fine ore/flux. The model solves rigorous conservation equations for all phases simultaneously, moreover the model was extended to consider six phases when injection of iron ore/flux was studied. The six-phases considered in this model are: gas, solid, hot metal, slag, pulverized coal and fine ore/flux. This model was applied to simulate the actual and several advanced blast furnace operations. Also the transient behavior of the blast furnace was investigated in two and three-dimensions. In order to take into account the changes in the solids particle diameter in the blast furnace, a degradation model, based on the solid motion, chemical reactions and physical properties of the solid particles, was developed. The fines generated by degradation process are considered in either fine ore/flux phase or pulverized coal phase. The fines generated from the coke particles are considered in the pulverized coal phase, while those generated from sinter, iron ore and pellets are assumed to joint to the fine ore/flux phase.

The model is based on the general conservation equation represented by Eq. (1), written in free coordinate form, which is used to model the conservation of phase momentum, mass and energy.

$$\frac{\partial(\varepsilon_i \rho_i \phi_i)}{\partial t} + \mathrm{div}(\varepsilon_i \rho_i \vec{U}_i \phi_i - \varepsilon_i \Gamma_\phi \,\mathrm{grad}\, \phi_i) = S_\phi \qquad (1).$$

Regarding source terms, the continuity and species conservation equations have mass sources due to chemical reactions and phase transformations. Momentum sources arise from inter-phase drag and either pressure gradients (for continuous phases *i.e.* gas and lump solids) or gravity (for discontinuous phases *i.e.* hot metal, slag pulverized coal and fine ore/flux). Enthalpy sources arise from inter-phase heat transfer, heat of reaction and sensible heat transfer accompanying mass transfer due to chemical reactions and phase transformations.

The blast furnace geometry is accurately represented by a body fitted curvilinear coordinate system. The governing equations are discretized over the whole blast furnace circumferential direction by using the control volume method. The model developed in this thesis uses improved numerical techniques which makes possible to solve the discrete equations more efficiently and faster. The use of covariant velocity projections in staggered arrangement allows faster convergence and better mass balance for all species. Phase properties are estimated using either pure component property calculated from theoretical models or semi-empirical correlations. Inter-phase drags and heat transfer rates are calculated from semi-empirical correlations. Rates of chemical reactions are from chemical kinetics and transport theory.

The model was applied to simulate the blast furnace process in the following conditions:

1. **Two-dimensional and transient behavior**: the model was validated using actual blast furnace data and in-furnace blast furnace temperatures measured by using sacrifice probe, which moves with the solid materials until melted down. The two-dimensional measured temperatures were compared with those predicted by the model. The simulations were performed on pulverized coal injection rates from 60 up to 250 kg/thm. The transient behavior of the blast furnace is predicted by assuming

an initial distribution of the dependent variables, and then, the model predicts variations of the inner furnace conditions throughout the time. The simulation results have shown that the blast furnace reaches the steady state, in which predicted inner temperature and operational parameters do not change significantly, after around 40 hours, when an arbitrary initial variable distribution were assumed. Comparison of calculated and measured temperature in all cases showed good agreement, which validates the model. Then, the model was used to investigate the effect of operational parameters such as burn-out ratio and changes of charging distribution pattern. The simulation results furnished useful information to design optimum blast furnace operations.

2. **Three-dimensional and transient analysis**: The three-dimensional blast furnace behavior is investigated by using the model developed in this thesis. The calculation was carried out in the whole circumferential direction while the raceways were uniformly distributed in this direction. Also the burden distribution was set up uniformly in the circumferential direction and varying in the radial direction. The purpose of this calculation was to prove that the blast furnace process presents three-dimensional behavior due to the discrete raceway distributions, which makes the creation of spot zones of high temperature and where coke is consumed by combustion reactions affecting strongly the motion of all phases in this region. The calculation results showed good agreement with the actual blast furnace data such as productivity, coke rate, slag rate and top gas analysis. In addition, three-dimensional behavior of the lower part of the blast furnace was revealed. Strong non-uniform distribution of the blast furnace variables such as solid, gas, liquids and powders motion were observed in the vicinity of the raceways. The three-dimensional transient behavior of the blast furnace is also investigated by using this model. The transient state of the blast furnace is investigated by analyzing the in-furnace conditions when the distributions of burden materials are abruptly changed. First the model predicted the steady state conditions for a given burden distribution, which gave an inverse V cohesive zone shape. Then, using the result as initial condition, the burden distribution was changed and the transient calculation set up. The model predicted the blast furnace variables until a new steady state was achieved, where a W shape of cohesive zone was predicted. The change in the cohesive zone shape investigated in this calculation was exclusively due to the burden distribution pattern, since all other parameters were kept constant. Therefore, the model predicted dynamically the in-furnace conditions starting form a inverse V cohesive zone shape, until a steady W shape cohesive zone was achieved. The simulation results shows that the blast furnace process needs about 20 hours to establish a new steady state when the burden distribution pattern is changed.

3. **Analysis of advanced blast furnace operations**: There exist increasing interest in the blast furnace operation with higher amount of tuyere injectants such as pulverized coal, fines of iron ore/sinter, fluxes and dust and auxiliary fuels such natural gas combined with pulverized coal. In this thesis the effect of such injectants to the blast furnace are analyzed. Firstly, the effects of the multiple injection of pulverized coal and iron ore/flux with oxygen enrichment was investigated by using the model. To consider ore/flux injection a new phase consisting of a mixture of iron oxides/gangue, CaO

and MgO was introduced and the conservation equations of momentum, energy and species for this phase was solved. Firstly only pre-reduced iron ore injection with oxygen enrichment was simulated, and in a second stage injection of fine pre-reduced iron ore together with fine flux was investigated. The simulation results showed that the blast furnace productivity could reach 4.5 t/day/m^3 while hot metal temperature was kept constant, and the silicon in hot metal was decreased to around 0.15 %. The coke rate also decreases to around 260 kg/thm. Secondly, the combined injection of natural gas and pulverized coal to the blast furnace was analyzed. The injection of natural gas is an established technology restricted to region with available natural gas, while the injection of pulverized coal is a current practice in the actual blast furnace operation. Aiming to take advantages of both practices, simultaneous injection of natural gas and pulverized coal with oxygen enrichment into the blast furnace was proposed in order to reach the following benefits: 1) Less energy consumption due to the replacement of the coke and corresponding increase of the production. 2) Environmental benefits due to the replacement of the carbon monoxide as reducing gas by the hydrogen contained in the natural gas. The efficiency of the reduction in the shaft of the blast furnace is expected to increase considerably due to natural gas injection, since natural gas contains a large amount of hydrogen, which replaces carbon monoxide and accelerates the reduction reactions in this region. Therefore less direct reduction occurs, which in turn, saves energy because this reaction is strongly endothermic. The simulation results showed that the hot metal production increased about 0.3 kg per each kg of natural gas injected, keeping constant hot metal temperature. The silicon in hot metal decreased to around 0.25%, coke rate decreased to about 280 kg/thm for natural gas injection of 120 kg/thm. Carbon in blast furnace off gas also decreases around 20 %, which could make the blast furnace process cleaner.

The major conclusions of this thesis are

1. A multi-dimensional transient blast furnace model has been developed which is able to simulate the blast furnace process in a 2-D or 3-D frame.
2. The model has been applied to simulate the actual blast furnace operation and several advanced operations.
3. The calculated results showed good agreement with 2-D steady state temperature distributions and operational parameters of actual operations. This model also predicts the three-dimensional and transient blast furnace operation successfully.
4. Simulation of advanced operations such as simultaneous injection of pulverized coal and natural gas or pre-reduced fine ore and flux through the blast furnace tuyeres showed that significant gain in productivity and energy savings could be obtained by using these practices.

Therefore, this model is considered as useful tool for design and optimization of the blast furnace operation, and is expected to contribute to increase the blast furnace performance by suggesting advantages of novel operation practices aiming to decrease the coke rate and increase the productivity.

審査結果の要旨

製鉄法の中核を成す高炉製銑法は、種々の操業改善により高効率化と省エネルギー化が達成されているが、依然として製鉄プロセスに投入される総エネルギーの約7割を消費している。プロセス内の消費エネルギーをさらに低減させるためには革新的な技術導入が不可欠であるが、このためには高炉炉内の諸現象を理論に基づき定量的に評価する方法が必要であった。本論文は、多流体理論に基づく高炉のプロセス解析技術の開発とこれを用いた新規操業技術の定量評価を試みたもので、全編7章からなる。

第1章は緒論であり、本研究の背景と目的および論文の構成について述べている。

第2章では炉内を流通する各物質の運動，伝熱，物質移動に関して多流体理論に基づいた非定常の支配方程式を示すとともに、反応，相変化および異相間相互作用を定式化して高炉プロセスの多次元数学モデルを提案している。このモデルは基本的には高炉製銑法のみならず充填層型反応プロセス全般に応用可能である。

第3章では前章で開発した数学モデルを羽口からの微粉炭吹き込み量の異なる数種の実炉操業の二次元解析に適用し、得られた結果を各種検出端情報と比較することでモデルの妥当性を示すとともに、各条件下での炉内状況を明らかにしており、現行操業法の改善について指針を与えるものである。

第4章ではモデルを三次元解析に応用し、炉内でも急激な温度および濃度の勾配が形成され溶銑品質に影響を与えると考えられる羽口近傍の物流の状態を明らかにした。炉下部の物流への三次元解析の適用は新しい試みであり、操業設計に対して有効な情報をもたらしている。非定常解析においては炉頂部へ供給される原燃料の分布形を変化させた場合に、その影響が炉内に伝播する傾向を明らかにしている。

第5章では羽口からの粉鉱石およびフラックス吹き込みの解析を行い、酸素富化を併用した粉鉱石とフラックスの同時吹き込みは、生産性と燃料比の大幅な改善ばかりでなく溶銑品質の向上も期待できることを示しており、解析で得られた炉下部の物流分布変化から粉鉱石吹き込みによるこれらの効果を説明している。

第6章では天然ガスおよび微粉炭の同時吹き込み操業のシミュレーションを行い、天然ガスによる炉内への水素の持ち込みは生産性の向上と温室効果ガス排出抑制に顕著な効果があること定量的に見いだしており、解析の範囲内では温室効果ガス抑制効果は約20％と予測している。

第7章は総括である。

以上要するに、本論文は多流体理論に基づいた非定常多次元の高炉プロセス解析技術を確立し、これを用いて新規操業技術の製造効率改善効果を定量的に評価したものであり、この新しい解析技術は金属プロセス工学の発展に寄与するところが少なくない。

よって、本論文は博士（工学）の学位論文として合格と認める。